On the burning of gas in a bubble

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***Abstract*— The problem on dynamics of hot gas bubble in a cold liquid was numerically solved. The model is based on two-dimensional laws of conservation for mass, pulse and energy in case of axial symmetry. The effects of gas turbulence were considered in the model as well. Processes of viscosity, heat conductivity, diffusion of substance, evaporation of a liquid on interface border were taken into account in the paper. The gas in a bubble is assumed to be compressible. The heat flux from the bubble into surrounding cold water was described in the model. The formulated problem with the stated boundary conditions was solved numerically by method of individual particles , which is updating of a method Harlow of particles in cells. The non-uniform numerical grid with a condensation near to an axis of symmetry was used. The computation algorithm provided a condensation of the grid in areas with the large gradients of parameters. Number of particles in cells is variable. The numerical algorithm provides an opportunity of association and splitting of individual particles belonging to the same body, depending on the current parameters of the medium. The maximal number of particles in a cell is equal to seven. The non-stationary fields of the basic thermodynamic parameters of gas within a bubble have been computed. It was found, that the pressure of gas in the bubble has the expressed tendency to recession, though at the initial moments of time its short-term increase is possible.**

***Index Terms*— bubble, evaporation, heat conductivity, modeling, pressure.**

I. INTRODUCTION

Transformation of chemical energy to heat is carried out in various boiler systems. The boiler principle of fuel burning (having aim of increase of specific capacities) is limited to problems connected to generation of film boiling on walls of the boiler, that results in the increased sizes of thermal systems. In papers [1,2] the method of burning of combustible gases directly in water with separate submission of combustible gas and oxidizer with the help of linear slot-hole nozzles was realized for the purposes of direct heating of the heat-carrier.

Combustion of fuel in bubbles is a complex multi-parametrical physical-chemical process. The complexity is caused by interface interaction of hot gas in bubbles and environmental cold liquid, in particular. For example, the dynamics of pressure of gas in a bubble after its ignition is not quite clear. This process is determined by differently working major factors. Cooling of gas in a bubble due to the heat outflow in a liquid owing to heat conductivity and also the energy losses for evaporation of a liquid on interface border objectively reduce values of gas temperature in a bubble and, hence, its pressure values. On the other hand mass of gas inside a bubble is increased for the account of phase transitions that can result in a growth of pressure. Determination of internal parameters of gas in a bubble is a difficult problem from experimental point of view, the estimated theoretical analysis is complicated by not adiabatic mode of a whole system.

The present paper is devoted to numerical modeling of interaction of hot gas in bubble with an environmental cold liquid.

II. STATEMENT OF THE PROBLEM

Let's consider a single gas bubble, which is in dynamic balance with a liquid (water) at initial pressure p_0 = 1 bar and temperature T_0 = 300K, the velocity of the media is equal to zero. At the instant $t_0 = 0$ gas in bubble blows up, and the values of its pressure and temperature achieve meanings p_1 and T_1 accordingly. It is required to determine meanings of gas parameters in the bubble at $t > 0$.

Let's assume, that the initial form of the bubble is spherical or сферична, or looks like ellipsoid. Therefore it is possible to consider the flow in an axial symmetry approximation, where the axis of symmetry is a large axis of ellipsoid. The axis z is directed along the large axis of an ellipsoid , and the axis r is normal to an axis z.

As interface border represents a boiling evaporating layer of water, then the flow of viscous heat-conducting compressible medium inside the bubble was described by non-stationary two-dimensional Reynolds equations for the conservation laws of mass, pulse and energy in view of turbulence effects:

$$\frac{\partial \mathbf{Q}}{\partial t} + \frac{\partial \mathbf{U}}{\partial r} + \frac{\partial \mathbf{F}}{\partial z} = \mathbf{G} \qquad (1)$$

Where the vector functions Q, U, F, G are described by the equations (2).

$$\mathbf{Q} = \begin{pmatrix} r\rho \\ r\rho u_r \\ r\rho u_z \\ rE \end{pmatrix}, \quad \mathbf{U} = \begin{pmatrix} r\rho u_r \\ r(\rho u_r^2 + p - \tau_{rr}) \\ r(\rho u_r u_z - \tau_{rz}) \\ r(E+p)u_r - r(u_r \tau_{rr} + \\ + u_z \tau_{rz} + q_r) \end{pmatrix},$$

$$\mathbf{F} = \begin{pmatrix} r\rho u_z \\ r(\rho u_r u_z - \tau_{rz}) \\ r(\rho u_z^2 + p - \tau_{zz}) \\ r(E+p)u_z - r(u_r \tau_{rz} + \\ + u_z \tau_{zz} + q_z) \end{pmatrix}, \qquad (2)$$

$$\mathbf{G} = (0,\ p - \tau_{rr},\ 0,\ 0).$$

$$E = \rho(e + q^2/2),\ e = p/((\gamma - 1)\rho),$$

$$q^2 = u_r^2 + u_z^2.$$

Here ρ, v_r, v_z, p, E are density, components of mass velocity of gas in a direction of coordinate axes r and z, pressure and total energy of unit of mass respectively; γ is adiabatic parameter.

The components of a vector of viscous tensions and components of a vector of a thermal flow are determined from ratios:

$$\tau_{ij} = \mu_e \left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i} - \frac{2}{3} \frac{\partial v_k}{\partial x_k} \delta_{ij} \right),$$

$$q_i = -\lambda_e \frac{\partial T}{\partial x_i}$$

Where μ_e, λ_e , T are effective viscosity, effective heat conductivity and temperature of gas, respectively.

μ_e is calculated as the sum of molecular μ and turbulent μ_t viscosity, λ_e is expressed through Prandtl number $\lambda_e = c_p(\mu/\mathrm{Pr} + \mu_t/\mathrm{Pr}_t)$, where c_p is a heat capacity at constant volume. Molecular and turbulent Prandtl numbers are constants (for air Pr = 0.72, Pr_t = 0.9).

For values of molecular viscosity the law of Sazerland is used:

$$\frac{\mu}{\mu_*} = \left(\frac{T}{T_*}\right)^{3/2} \frac{T_* + S_0}{T + S_0}$$

Where μ_* = 1.68 10-5 kg / (m s), T* = 273 K, S_0 = 110 K for air.

The description of turbulence was carried out with the help of two-parametrical k-ε model. For transition of turbulent kinetic energy k and the velocity of its dissipation ε the following equations are valid:

$$\frac{\partial \rho k}{\partial t} + (\rho v \cdot \nabla)k = \nabla\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\nabla k\right] +$$
$$+ P - \rho\varepsilon,$$
$$\frac{\partial \rho\varepsilon}{\partial t} + (\rho v \cdot \nabla)\varepsilon = \nabla\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\nabla \varepsilon\right] +$$
$$+ \frac{\varepsilon}{k}(C_{\varepsilon 1} P - C_{\varepsilon 2}\rho\varepsilon).$$

Where the characteristic constants accept the values: σ_k = 1.0, σ_ε = 1.3, $C_{\varepsilon 1}$ = 1.44, $C_{\varepsilon 2}$ =1.92. The turbulent viscosity is calculated according to Kolmogorov-Prandtl formula:

$$\mu_t = \frac{C_\mu \rho k^2}{\varepsilon}, \quad C_\mu = 0.09.$$

The turbulent coefficient P is calculated from the ratio: $P = \mu_t |S|^{1/2} |\Omega|^{1/2}$. The invariants of tensor of deformation velocities and the tensor of rotation look like:

$$|S| = (2 S_{ij} S_{ij})^{1/2}, \quad |\Omega| = (2\Omega_{ij}\Omega_{ij})^{1/2}, \text{ где}$$

$$S_{ij} = \frac{1}{2}\left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i}\right), \quad \Omega_{ij} = \frac{1}{2}\left(\frac{\partial v_i}{\partial x_j} - \frac{\partial v_j}{\partial x_i}\right).$$

The variation of water vapor concentration C inside a bubble was described with the help of the diffusion equation:

$$\frac{\partial(r\rho C)}{\partial t} + \frac{\partial(r\rho u_r C)}{\partial r} + \frac{\partial(r\rho u_z C)}{\partial z} =$$
$$= r\rho D\left(\frac{\partial^2 C}{\partial r^2} + \frac{1}{r}\frac{\partial C}{\partial r} + \frac{\partial^2 C}{\partial z^2}\right), \qquad (3)$$

Where D is a diffusion coefficient.

We consider that on interface border stick condition is valid. For the description of intensity of evaporation I (kg / m^{2}s) the following empirical formula is used:

$$I = P_* \mu (0{,}734 + 1{,}637 v_*) 10^{-6} \qquad (4)$$

Here P* is pressure of saturated vapors паров at fixed temperature (кPa), v* is velocity of gas.

The bottom border of calculation region is axis of symmetry of the bubble. The formulated problem with the stated boundary conditions (1) - (4) was solved numerically by method of individual particles [3], which is updating of a method Harlow of particles in cells. The non-uniform numerical grid with a condensation near to an axis of symmetry was used. The computation algorithm provided a condensation of the grid in areas with the large gradients of parameters. Number of particles in cells is variable. The numerical algorithm provides an opportunity of association and splitting of individual particles belonging to the same body, depending on the current parameters of the medium. The maximal number of particles in a cell is equal to seven.

III. THE RESULTS OF CALCULATIONS

Let assume that at the moment t = 0 bubble is filled with air at initial values p_1 = 9 bar, T_1 = 2700 K, ρ_1 = 1.204 kg / m^3, γ = 1.4. To escape one-dimensional mode of the flow it is assumed that the bubble is placed in a hole of the thin vertical metal plate.

In fig. 1 the calculated map of mass concentration of water vapor C inside the bubble is submitted at instant t = 1 ms. For this moment the minimal value of concentration C = 0 is achieved at the centre of the bubble, the maximal one C = 1 is achieved at its border with water. The region of mixing represents a narrow layer at interface border.

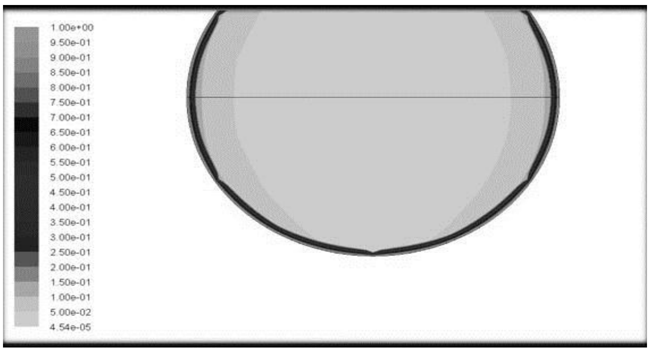

Fig. 1. Distribution of mass concentration of water vapor in the bubble.

In fig. 2 the distribution of mass velocity of gas in bubble at the same moment of time, as for a fig. 1 is represented. It is

visible in the figure, that inside the bubble intensive enough convective processes occur. The minimal values of gas velocity U = 0 are achieved at the centre of the bubble and on interface border. The maximal value U = 5,98 m/s takes place in area located approximately on distance of half of bubble radius from its centre.

In fig. 3 the results of numerical modeling for gas density in the bubble (kg / m^3) are submitted. It is visible, that average density of gas in the bubble has increased approximately by 8 % due to evaporation process. If at the centre of the bubble density values remain close to initial meanings (ρ = 1.2 kg / m^3), then on interface border it achieves maximal one at that instant ρ = 1.43 kg / m^3.

The calculated map of gas temperature (K) inside the bubble is represented in fig. 4. Distribution of temperature here is monotonous enough. The maximal meaning T = 2700 K coincides with initial one and takes place at the centre of the bubble, the minimal meaning T = 300 K is realized on interface border and is equal to temperature of water

The results of numerical modeling for gas pressure (bar) inside the bubble are represented in fig. 5. It is visible, that waves of pressure in this case are weak, and distribution of this thermodynamic parameter is uniform enough. The maximal meaning of pressure at this moment of time p = 8.61 bar takes place at the centre of the bubble, and the minimal one p = 8.59 bar is in a vicinity of interface border. If at the initial moments of time the pressure of gas in the bubble grows a little bit, then by that moment the fall of pressure inside the bubble is appreciable enough and makes approximately 5,6 % from initial one.

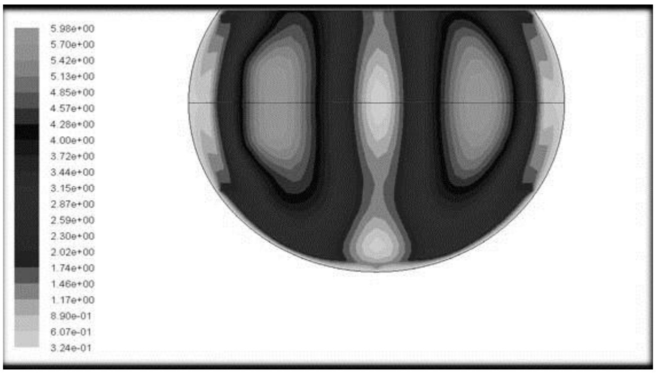

Fig. 2. Results of numerical simulation of gas velocity U in the bubble (m/s).

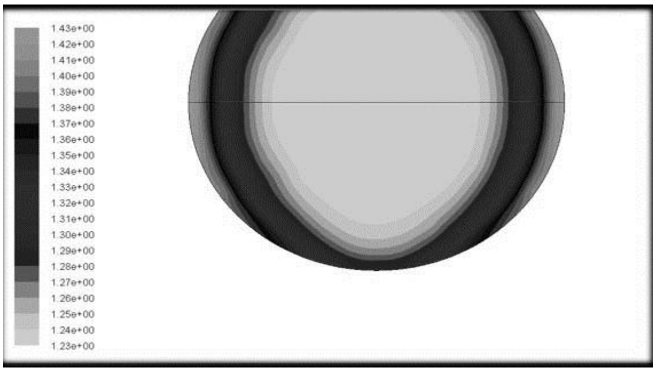

Fig. 3. Density of gas map in the bubble

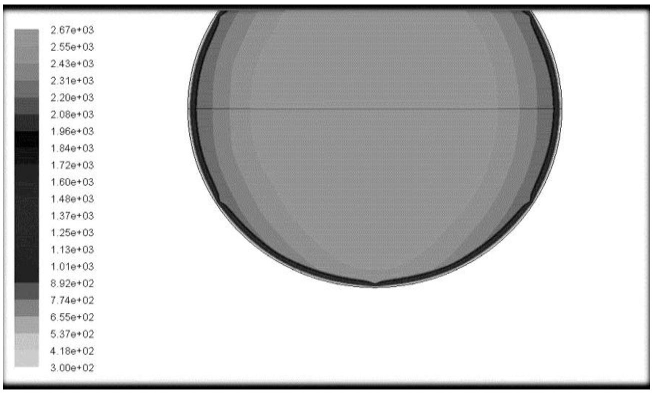

Fig. 4. Values of temperature of gas in the bubble

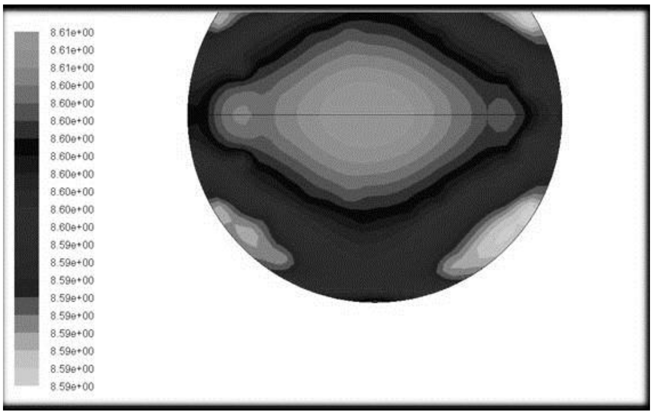

Fig. 5. Pressure of gas map in the bubble.

IV. CONCLUSION

Thus, in the paper the numerical modeling of variation of values of thermodynamic parameters of gas in the bubble in conditions of phase transitions on interface border is performed. The model is based on two-dimensional laws of conservation for compressible viscous and heat-conducting gas. The phenomenon of turbulence and diffusion of substance are taken into account as well. It was found, that the pressure of gas in the bubble has the expressed tendency to recession, though at the initial moments of time its short-term increase is possible.

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